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Potential of energy savings and CO_2 emission reduction in China's iron and steel industry

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HIGHLIGHTS

- Analyze potential of energy and CO_2 reductions in China's iron and steel industry.
- A National Energy Technology—Iron and Steel (NET-IS) model is developed.
- Potential CO_2 emission reductions could achieve 818.3 $MtCO_2$ during 2015–2030.
- Promoting low-carbon technologies is the most effective way for emissions reduction.
- Emission abatement cost would be 1740 CNY/CO_2 in 2030 in iron and steel industry.

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ABSTRACT

The iron and steel industry plays an important role in mitigating global climate change. As the largest steel producer and consumer, China bears the primary responsibility for energy savings and CO_2 emission reduction in the iron and steel industry. In this study, taking China as the empirical context, we analyze the effectiveness of the following four strategies on the potential of energy savings and emission reduction: phasing out backward production capacity in accordance with the current major policies, adjusting the production structure to increase electric arc furnace steelmaking, promoting low-carbon technologies, and switching to clean fuels. Under the principle of cost minimization, the mitigation potential of different strategies until 2030 and the technological development paths for reducing energy and CO_2 emissions in China's iron and steel industry are identified via an established National Energy Technology model. The results show that promoting low-carbon technologies is the most effective strategy for energy savings and emission reduction alongside cost minimization. Compared with existing policies, these strategies could lead to a cumulative reduction of 818.3 $MtCO_2$ (4.1%) during the period 2015–2030. Therefore, policy makers should provide financial or administrative support to promote the development of specific production and low-carbon technologies such as non-blast furnace iron-making and endless strip production.

1. Introduction

The IPCC fifth assessment report has clearly pointed out that climate change is caused by anthropogenic greenhouse gas emissions, and poses a threat to human society and natural ecosystems [1]. Therefore, effective adaptation and mitigation measures are necessary. To address climate change, key sectors such as industry, transportation, construction, and agriculture need low-carbon transformation. As one of the most resource-intensive industries, the iron and steel industry is a major sector of greenhouse gas emissions accounting for about 7% of total global CO_2 emissions [2]. In 2016, world total crude steel output was 1.63 billion tons, while China's crude steel production reached 808.4 million tons, accounting for 49.6% of global output (Fig. 1). The apparent consumption of finished steel reached 1.52 billion tons globally, with China accounting for about 45.0% in 2016 [3]. At present, China has become the world's largest steel producer and consumer [4]. Furthermore, energy consumption in China's iron and steel industry is dominated by coal and coke which accounts for 89.18% of energy consumption in the iron and steel industry [5]. This makes the iron and steel industry the main CO_2 emitters in China, contributing

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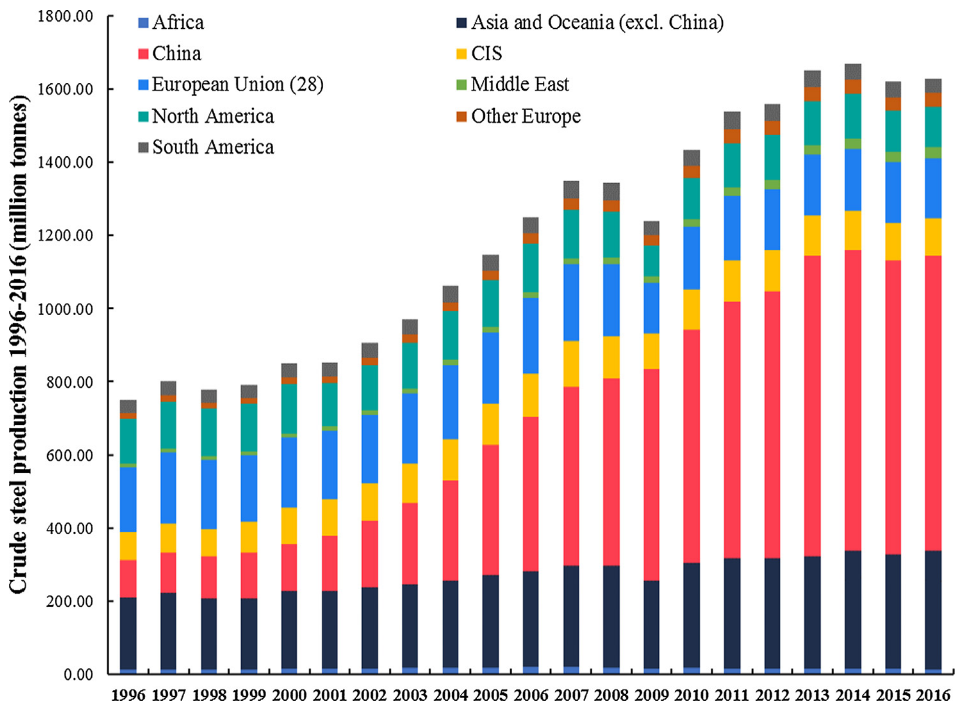

Fig. 1. Crude steel production around the world from 1996 to 2016.

approximately 15% of national CO_2 emissions [6]. Therefore, the development of the iron and steel industry is facing serious environmental problems [7], and the transition to low-carbon technologies is of great significance for controlling CO_2 emissions and implementing commitments to emission reduction [8].

China's iron and steel industry is driven by domestic demand. With the rapid development of the economy and urbanization, the iron and steel industry has grown vigorously. Alongside the national policy of phasing out backward production capacities and applying new technologies, comprehensive energy consumption per tonne of steel production has dropped substantially in the past few decades [9]. However, the overall energy efficiency of China's iron and steel industry remains relatively low compared with countries with advanced technologies. This is mainly because of China's outdated production equipment, poor energy efficiency among small enterprises, and low secondary energy recovery rate [10]. Therefore, the introduction of advanced technologies and equipment is an effective way to enhance the energy efficiency of the iron and steel industry [11].

Recently, CO_2 emissions in China's iron and steel industry have increased year by year [12]. To achieve energy savings and CO_2 emission reduction in the iron and steel industry, the government has promulgated a series of policies, including the following: (1) eliminating backward production and prohibiting new capacities (e.g., blast furnaces of 400 m^3 and less) [13,14]; (2) developing electric arc furnace (EAF) steelmaking, implementing green upgrading and innovation, and promoting technological innovation [15,16]; (3) popularizing removal or recovery technologies, such as sintering efficient dust removal systems, dry removal of converter flue gas dust, waste heat recovery and others [13]; and (4) establishing strict environmental standards and emissions targets [17,18]. National policies have provided an important guarantee for the sustainable development of the iron and steel sector in China.

Until now, many studies have investigated the potential of CO_2 emission reduction that China's iron and steel industry can achieve by considering some of the above-mentioned policies. However, most of those studies over-simplified the steel production process and lack detailed descriptions of the energy-consuming technology inventory, and thus cannot comprehensively evaluate the impacts of the latest national plans, industrial standards, and international frontiers on the iron and steel industry. The present study aims to provide a more concrete picture on the steel production process and relevant technologies, and to analyze the effectiveness of four energy-saving and CO_2 emission reduction strategies on China's iron and steel industry. These strategies include: following the current policies scenario, which focus on phasing out backward production capacities (business-as-usual [BAU]); adjusting the production structure by further raising the proportion of EAF steelmaking in addition to the BAU scenario (PS); further promoting low-carbon technologies in addition to the PS scenario (LT); and switching to clean fuels by reducing coal consumption in addition to the LT scenario (CF). As can be seen, the CF scenario is a combination of all four strategies. To evaluate the effectiveness of these strategies, we further develop a National Energy Technology-Iron and Steel (NET-IS) model with the objective of cost minimization during the procedure of steel production. The NET-IS model describes the decision-making process for the selection of different production technologies throughout the steel production process, and then calculates and analyzes the corresponding energy use, emissions, and required investment costs for meeting demand. The results provide a more manipulable technology development path that could better instruct policy design and technology deployment for reducing energy consumption and CO_2 emissions in the iron and steel industry.

The layout of the present paper is as follows. In Section 2, we briefly review previous work related to the energy and emissions of the iron and steel industry. In Section 3, we introduce our method, which includes the details, architecture, and equations of the NET-IS model. In Section 4, we analyze the settings for the four scenarios and the parameters established in the NET-IS model. In Section 5, we show the projection results in terms of the CO_2 emissions, costs, energy consumption, and technology path. Finally, in Section 6, we draw conclusions and discuss some policy implications.

2. Literature review

As an important sector of energy consumption and CO_2 emissions, the iron and steel industry has become one of the most popular target sectors for scholars. Many scholars have explored the main drivers of

energy consumption and CO_2 emissions, and found that economic activity, energy structure, energy efficiency and the improvement of production technologies are the primary driving factors that affect CO_2 emissions in the iron and steel sector [19,20]. For example, Yu et al. discussed the impact of economic growth, technological progress, and investment expansion on the iron and steel sector's CO_2 emissions using vector autoregression (VAR) and Granger tests. Their results show that technology investment can significantly reduce carbon emissions [21]. Xu et al. used the quantile regression model to explore the driving forces of CO_2 emissions in the iron and steel industry in China's different provinces from 2000 to 2015. The results show that the optimized economic structure, the development and application of energy-saving and emission reduction technologies and increased clean energy sources are key measures for saving energy and reducing CO_2 emissions in China's iron and steel industry [12]. Xu et al. verified that the improvement of energy efficiency is the most important and influential factor for reducing CO_2 emissions in China's iron and steel industry, using the VAR model [22]. Wei et al. used a Malmquist Productivity Index (MPI) decomposition to study the energy efficiency of China's iron and steel industry from 1994 to 2003. The results show that energy efficiency increased by 60%, with technological improvement being the major factor [11]. These studies emphasize the critical role of increasing capital investment for advanced technologies and improving the energy efficiency of technologies in the development of low-carbon technologies for the iron and steel industry.

Therefore, many scholars analyze CO_2 emission reduction from the aspects of industrial processes and technologies in the iron and steel industry by evaluating the potential of CO_2 emission reduction and investment costs under different technology portfolios. These studies are mainly fulfilled by an economic evaluation of engineering and the bottom-up model. Hasanbeigi et al. evaluated the costs, energy savings, and commercialization of 12 emerging technologies that are used to replace traditional ironmaking technologies [23]. Kuramochi investigated the production processes of blast furnace-basic oxygen furnace (BF-BOF) and EAF in Japan and evaluated the use of scrap in BF-BOF. They found that adding scrap to BF-BOF not only stimulates the scrap market, but also reduces CO_2 emissions [24]. Zhang et al. calculated energy intensity using the future market penetration rates of energy-saving technologies in China to obtain energy consumption and CO_2 emissions. They analyzed detailed data on 28 energy-saving technologies and discussed the impact of improvements in energy efficiency and changes in the production structure on energy consumption [25]. These provide the basis for the collection of technology data in the present study.

Table 1 lists several studies that used bottom-up technological methods to analyze energy consumption or CO_2 emissions from the iron and steel industry in different countries. The methods used are mainly accounting or linear optimization models. However, the existing literature does not describe production and energy-saving technologies in the iron and steel industry in China in detail. More specifically, for the consideration of low-carbon technologies in Table 1, Ates [27] calculated the energy-saving potential of Turkey in terms of improving management capabilities and establishing an energy management center, and Brunke and Blesl [28] assessed the CO_2 emission reduction potential of 32 energy-saving technologies in Germany's iron and steel industry. Considering China's specific low-carbon technologies, Wen et al. [30], Chen et al. [32] and Ma et al. [33] analyzed the energy-saving potential of 21, 10, and 28 energy-saving technologies in China, respectively. However, those studies lacked a high-resolution consideration of technology development, for example, the process of non-blast furnace ironmaking (direct reduction ironmaking [DRI] and smelting reduction ironmaking [SRI]) and pellet production, as well as some low-carbon technologies, such as pellet sintering and pellet waste heat recycling, are not discussed. Meanwhile, the existing optimization model lacks assessments of different energy-saving policies emphasized in China's iron and steel sector, such as the effectiveness of phasing out

Table 1
Existing literatures on CO_2 emissions of iron and steel industry based on bottom-up model.

Authors	Year	Method	Country	Key factors	Results years	Main contents	Findings	Ref.
Wang et al.	2007	Long-range Energy Alternatives Planning (LEAP) system	China	Industrial structure Improvement of blast furnace Coke dry quenching (CDQ) Energy management center	2020	CO_2 emission reduction	24.63 $MtCO_2$ (million tonnes of CO_2) 3.52 $MtCO_2$ 3.64 $MtCO_2$	[26]
Ates	2015	LEAP system	Turkey	Acceleration of energy efficiency improvement Cleaner production	2010–2030	Change rate of energy intensity	−38% 51%	[27]
Brunke and Blesl	2014	Fuel (FCCC) and electricity conservation cost curves (ECCC)	Germany	Development of advanced technologies	2013–2035	Annual energy savings	92.74 PJ per year	[28]
Karali et al.	2014	Industry Sector Energy Efficiency Modeling (ISEEM)	The United States of America	Consumption of low-emission fuels and increase of EAF	2010–2035	Share of energy costs in the total costs	Decrease from 16% in 2010 to 11% in 2035	[29]
Wen et al.	2014	The Asian-Pacific Integrated Model/ Enduse (AIM/Enduse)	China	Increase of EAF and promotion of advanced technologies	2010–2020	Average energy consumption of the EAF Average energy consumption of the BF-BOF	0.30 tce/t crude steel 0.50 tce/t crude steel	[30]
Dutta and Mukherjee	2010	MARKAL	India	Installation of pulverized coal injection, improvement of blast furnace control system, and sensible heat recovery	2030	Total CO_2 emission reduction potential in 2030	8%	[31]
Chen et al. Ma et al.	2014 2016	The Integrated MARKALEFOM System (TIMES)	China	Application of specific energy conservation technologies and EAF	2010–2050	Changes in CO_2 intensity	From 2241 $kgCO_2/t$ in 2010 to 1346 $kgCO_2/t$ in 2050	[32,33]

backward production capacities.

Therefore, the present paper collects the latest inventory and technical parameters of steel production technologies according to the detailed classifications mentioned in national plans, industrial standards, and the international frontier, which includes 36 different sizes of production technologies and 24 kinds of low-carbon technologies. Compared with existing studies, we contribute a more concrete picture of the production process and relevant technologies that are closer to actual practice in the iron and steel industry. On the basis of this, we build a NET-IS model to predict energy consumption and CO_2 emissions in China's iron and steel industry from the perspective of the steel production process. Meanwhile, we further explore the optimal path of technological development under different policy strategies for energy savings and emission reduction in China's iron and steel industry, including phasing out backward production capacities in accordance with current major policies, adjusting the production structure to increase EAF steelmaking, promoting low-carbon technologies, and switching to clean fuels. The high-resolution classification of technologies could provide a more accurate assessment of the effects of these policy strategies allowing a more straightforward technology development path for guiding the practice.

3. Methodology

3.1. National Energy Technology (NET) model

To fulfill this analysis, we developed a NET model, which is a bottom-up energy technology selection model developed by the Center for Energy and Environmental Policy Research at the Beijing Institute of Technology. It can evaluate the emission reduction potential of different policies based on the industry's production technologies. With a description of the market raw material supply, energy price change, technological progress, energy structure adjustment, emissions constraint and other factors, the NET model seeks to explore the optimal technology development path that can meet future service demand at a minimum cost. The NET model can be used to simulate the material and energy flows in different sectors during the production or consumption process. The corresponding energy consumption and emissions in each sector can then be calculated, providing an instrument for evaluating the effect of sustainable development policies in a straightforward manner. On this basis, we can further answer the questions of what technology pathways are required to achieve environmental targets, as well as the potential of emission reduction and abatement costs under a combination of different technologies. Fig. 2 shows the structure of the NET model, which includes a data module, a service demand projection model, a technology-energy-environment model, a green policy module, and an output module.

Until now, the NET model has established seven sub-models for seven sectors with the most intensive energy consumption and CO_2 emissions. It includes NET-IS for the iron and steel industry, NET-Cement for the cement industry, NET-Power for the power industry, NET-Chemical for the chemical industry, NET-Transport for the transportation sector, NET-Residential for the residential sector, and NET-Building for the commercial building sector (Fig. 2).

This paper uses the NET-IS model to analyze the potential of CO_2 emission reduction and the operable technology development path for China's iron and steel industry. The energy savings and CO_2 emission reduction policies considered in this study refer to the existing policies related to technology substitution and upgrades (adopting large-scale or advanced production equipment to replace traditional small-scale or backward production equipment), fuel conversion, and advanced technology retrofitting (attaching low-carbon technologies to existing technologies to improve energy efficiency) in the iron and steel industry.

3.2. NET-IS model

The NET-IS model is an optimization model. For this study, three steps are included in the model: projection of steel production demand in future years, selection of production technologies to meet the steel demand, and calculation of energy consumption and CO_2 emissions.

3.2.1. Objective function

The objective function is to minimize the total cost per year. The total cost here consists of three parts: the average annualized investment cost of steel equipment, operation and maintenance costs, and additional carbon tax and energy tax.

$$TC_t = IC_t + RC_t + EC_t \tag{1}$$

where TC_t is the total cost of steel equipment in year t; IC_t is the initial cost, which is annualized to year t, see Eq. (2) [34]; RC_t is the operating cost in year t, which mainly includes equipment maintenance cost and energy purchased cost; and EC_t is the energy tax and carbon tax in year t.

$$IC_t = \sum_l C_{t,l}\cdot(1-SIC_{t,l})\cdot\frac{r(1+r)^{T_l}}{(1+r)^{T_l}-1} \tag{2}$$

where $C_{t,l}$ denotes the total initial investment cost of newly installed device l in year t; $SIC_{t,l}$ denotes the subsidy rate of initial investment of device l in year t; r means the discount rate of the iron and steel sector; and T_l is the lifetime of device l.

Regarding the operation cost, considering improvements in future energy efficiency and the possibility of implementing subsidies, RC_t could be further formulated as:

$$RC_t = \sum_l \left(OC_{t,l} + \sum_k P_{t,k}\cdot E_{t,k,l}\cdot(1-\eta_{t,l}) + \sum_n P_{t,n}\cdot RM_{t,n,l}\cdot(1-\lambda_{t,l})\right)\cdot (1-SRC_{t,l})\cdot X_{t,l} \tag{3}$$

where $OC_{t,l}$ means the non-energy operating costs of device l in year t (e.g., maintenance, management fees, etc.); $P_{t,k}$ indicates the energy price of energy k in year t; $E_{t,k,l}$ indicates the amount of energy k consumed by device l in year t; $\eta_{t,l}$ is the energy efficiency improvement rate of device l in year t; $P_{t,n}$ indicates the price of raw material n in year t; $RM_{t,n,l}$ indicates the amount of purchased raw material n consumed by device l in year t; $\lambda_{t,l}$ is the raw material efficiency improvement rate of device l in year t; $SRC_{t,l}$ is the subsidy rate of device l in year t; and $X_{t,l}$ is the operating number of device l in year t.

Energy and emissions taxes are designed to represent the external environmental costs of fossil energy and gas emissions, and we can set different energy and emissions taxes based on the energy consumption and emissions required by the equipment, taking into account the depletion rate of incomplete combustion of the equipment.

$$EC_t = \sum_l \sum_k \{\sum_g [\lambda_{t,g}\cdot X_{t,l}\cdot(e^0_{t,g,l} + e^k_{t,g,l}\cdot E_{t,k,l}\cdot(1-\eta_{t,l})\cdot\delta^k_{t,l})] + [\lambda_{t,k}\cdot E_{t,k,l}\cdot(1-\eta_{t,l})\cdot X_{t,l}]\} \tag{4}$$

where $\lambda_{t,g}$ means emissions tax levied on gas g in year t; $\lambda_{t,k}$ means energy tax levied on energy k in year t; $e^0_{t,g,l}$ denotes the emissions of gas g generated by non-energy consumption (process emissions) of device l in year t; $e^k_{t,g,l}$ denotes emissions of gas g generated by consumption of fuel type k when using device l in year t; and $\delta^k_{t,l}$ is the burning rate of energy k owing to insufficient combustion of device l at year t.

3.2.2. Model constraints

The main constraints in addition to the objective function considered in this study include the constraints on future steel demand, energy supply, and consumption owing to resource limitations or policy orientation, internal material and energy flows in the production process, and the numbers of retrofitted or recruited devices. The details are

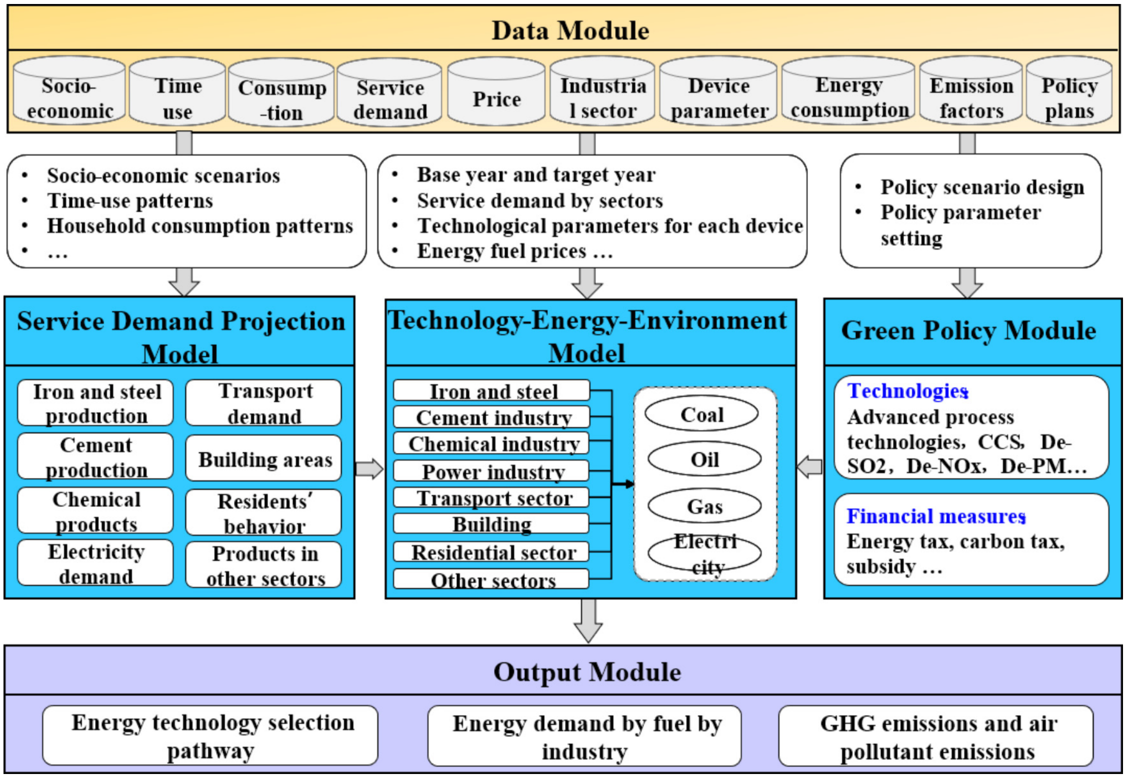

Fig. 2. Structure of NET model.

explained as follows.

(1) Steel demand constraints (Eq. (5)): the results of the model must be based on meeting the future demand of steel in the whole of society.

$$\sum_l X_{t,l} \cdot O_{t,l} \cdot (1+\varepsilon_{t,l}) \geqslant D_t \tag{5}$$

where $O_{t,l}$ means the steel output per operation of unit device l in year t; $\varepsilon_{t,l}$ is the improvement rate of production efficiency for unit device l in year t; and D_t means the demand for steel in year t.

(2) Energy supply and consumption constraints ((Eq. (6)): the energy consumption in the iron and steel industry needs to consider the maximum and minimum supply limits or policy constraints for different energy varieties.

$$E_{t,k}^{\min} \leqslant \sum_l E_{t,k,l} \cdot (1-\eta_{t,l}) \cdot X_{t,l} \leqslant E_{t,k}^{\max} \tag{6}$$

where $E_{t,k}^{\max}$ indicates the maximum supply or consumption of energy k in year t; and $E_{t,k}^{\min}$ means the minimum supply or consumption of energy k or in year t.

(3) Conversion constraint of internal products and energy ((Eq. (7)): when the intermediate products produced in the previous production process enter the next stage as input raw material or energy, the amount of input raw material or energy in the next stage should be no more than the intermediate products produced in the previous stages.

$$\sum_l X_{t,l,s} \cdot O_{t,l,s} \cdot (1+\varepsilon_{t,l}) \geqslant \sum_{l'} M_{t,l',s} \cdot (1-\beta_{t,l'}) \cdot X_{t,l',s} \tag{7}$$

where $X_{t,l,s}$ is the operating number of device l in year t for producing the intermediate product s; $O_{t,l,s}$ means the output s per operation of unit device l in year t; l' denotes device l' that consumes intermediate product s produced in the previous stages; $M_{t,l',s}$ denotes the amount of intermediate product s that unit device l' consumes in year t; $X_{t,l',s}$ is the operating number of device l' in year t that consumes the intermediate product s; and $\beta_{t,l'}$ means the input raw material or energy reduction rate for device l' in year t.

(4) Operating rate ((Eq. (8)): the operating number of device l in year t equal to the product of the operating rate and the amount available to run.

$$X_{t,l} = \theta_{t,l} \cdot S_{t,l} \tag{8}$$

where $\theta_{t,l}$ denotes the operating rate of device l in year t; and $S_{t,l}$ denotes the total number of device l in year t.

(5) Dynamic change of number of device l ((Eq. (9)): the stock of device l in year t equals the stock of device l in year t-1 plus the amount of newly recruited device l in year t, and minus the retired amount of device l in year t.

$$S_{t,l} = S_{t-1,l} \cdot (1-\frac{1}{T_l}) + n_{t,l} - r_{t,l} \tag{9}$$

where T_l denotes the lifetime of device l; $n_{t,l}$ denotes the amount of the newly recruited device l in year t; and $r_{t,l}$ denotes the retired amount of device l in year t.

(6) New equipment constraints ((Eqs. (10) and (11)): the newly recruited devices should meet the efficiency standard, in other words, there is a constraint for the number of newly recruited devices with high and/or low efficiency (e.g., new small- and medium-sized blast furnaces, converters, and EAFs should meet the basic technological efficiency standards required by the iron and steel industry).

$$\omega_{t,l}^{\min} \leqslant n_{t,l} \leqslant \omega_{t,l}^{\max} \tag{10}$$

where $\omega_{t,l}^{\max}$ denotes the maximum amount of newly recruited device l in year t; and $\omega_{t,l}^{\min}$ denotes the minimum amount of newly recruited device l in year t. If there is no restriction, $\omega_{t,l}^{\min} = 0$ and $\omega_{t,l}^{\max} = 100\%$.

The number of newly recruited device l in year t needs to meet the

new device growth rate constraint.

$$(1+\gamma_{t,l}^{\min})\cdot n_{t-1,l} \leqslant n_{t,l} \leqslant (1+\gamma_{t,l}^{\max})\cdot n_{t-1,l} \tag{11}$$

where $\gamma_{t,l}^{\max}$ indicates the maximum annual growth rate of new device l in year t; and $\gamma_{t,l}^{\min}$ indicates the minimum growth rate of new device l in year t.

(7) Stock constraint of steel production devices: in the target year, the stock of device l needs to meet the stock limitation following the policy trends after excluding the retired or replaced devices (e.g., elimination of outdated production capacity and the equipment required to be eliminated in the study year to complete the phase-out task).

$$\psi_{t,l}^{\min} \leqslant S_{t,l} \leqslant \psi_{t,l}^{\max} \tag{12}$$

where $\psi_{t,l}^{\max}$ denotes the maximum stock of device l in year t; and $\psi_{t,l}^{\min}$ denotes the minimum stock of device l in year t.

3.3. Steel production process in the NET-IS model

In the NEI-IS model, CO_2 emissions are mainly from fuel combustion (coal, oil, natural gas, etc.) and electricity for running the devices in each technological process, such as in ironmaking processes, blast furnaces consume fuels and electricity to produce hot metal. There is also a small proportion of CO_2 produced by the decomposition of raw materials, such as limestone as the solvent, which produces CO_2 during the firing process.

Fig. 3. shows the simplified steel production process described in the NET-IS model. In this figure, different colored frames represent the different steel industrial processes. The white text boxes represent traditional production technologies, and the low-carbon technologies in each process are represented in a text box with the same color as the industrial process. There are two main routes for producing steel products: the BF-BOF route (primary route) and the EAF route (secondary route). The BF-BOF route and the EAF route can be replaced with each other because both can be used to produce crude steel to meet future steel demand. The main difference between these two routes is that they use different raw materials. The BOF route uses molten iron as the main raw material, whereas the EAF route uses scrap. In the BF-BOF route, the production of hot metal requires the coke produced in the coking process to provide heat and the sintering/pelletizing process to produce sinter/pellet as the raw material. The coking and sintering/pelletizing processes consume large amounts of coal as raw materials and energy, and produce a large amount of CO_2. In the EAF route, recycled scrap is used as the main raw material. The processes of producing molten iron are omitted and the consumption of coal is saved. The EAF route uses electricity as its main energy source, which is cleaner. Therefore, compared with the BF-BOF route, the EAF route provides more energy savings and CO_2 emission reduction. The low-carbon technologies refer to the technologies that recover heat for power generation or reheating and improve energy efficiency; for example, sintering waste heat recovery technology, which recycles the heat of exhaust gas generated during the sintering process and can be further used for heating and power generation. The main processes and technologies used in each process for steel production are listed in Table 2, and a detailed technical introduction is given in Appendix A. From a technological viewpoint, the core of low-carbon or green development in iron and steel mills relies on the use of steel production technologies, devices for improving energy efficiency and various emission-control technologies. In other words, it comes to a decision-making problem of determining different technology combinations. Therefore, to reduce the impact of steel production on the environment, we should turn our attention to technology deployment during the steel production process.

At present, in the BF-BOF production process, blast furnace ironmaking generates a large amount of CO_2 emissions owing to the consumption of coke (the coking process), coal and sinter (the sintering process), or pellets (pellet process production). A newly developed non-blast furnace ironmaking process that includes both direct and smelting reduction methods is considered an alternative solution. The direct reduction method refers to the ironmaking process of reducing iron ore to sponge iron using natural gas or coal below the melting temperature as a reducing agent, the product of which is DRI. The current development process includes Midrex, Hylsa, and other methods. Smelting reduction refers to the method of reducing iron ore at high temperatures without using a blast furnace. The Corex smelting reduction method has been commercialized, and the Hismelt method is still in semi-industrial testing. Non-blast furnace ironmaking reduces the necessary emissions from sintering, pellet process production, and coking process, and has the advantage of reducing CO_2 emissions [35]. However, blast furnace production is still far superior to non-blast furnace production in terms of technology, economy, and scale [36]. As the technology becomes more developed in the future, non-blast furnace ironmaking will gradually enter the ironmaking process to replace the traditional blast furnace ironmaking process.

There are three technological channels to save energy and reduce emissions in the BF-BOF and EAF processes: (1) adopting large-scale advanced production equipment or internationally advanced equipment to replace traditional small-scale backward production equipment (the replacement of the same type of equipment for each process), which are listed in the second column of Table 2; (2) retrofitting the existing technologies or adding low-carbon technologies to improve energy efficiency, such as coke quenching technology, blast furnace pulverized coal injection, and electric furnace flue gas waste heat recovery technology, which are listed in the third column of Table 2; and (3) introducing advanced production routes to replace traditional routes, such as shifting to EAF production from the BF-BOF route. The NET-IS model seeks the economically optimum technology development path and selects different combinations of production and low-carbon technologies to project future CO_2 emissions.

4. Scenario design

4.1. Scenario definition

During the “Eleventh Five-Year Plan” and “Twelfth Five-Year Plan” periods, China stepped up its efforts to eliminate backward production capacities. Major measures include the phase-out of small-scale inefficient production equipment, such as blast furnaces of 400 m^3 and less [18].

In addition to closing down small and backward production facilities, CO_2 emission reduction in China’s iron and steel industry is dependent on changes in product mix shift from BF-BOF to EAF production. In 2015, China’s crude steel production by BF-BOF accounted for 93.9% of the total, while that by EAF accounted for only 6.1%, which is much lower than the global average of 25.2% [3]. In the coming decades, the growth of China’s crude steel production by EAF can be foreseen [37].

Micro-level low-carbon technologies also play an important role in emission reduction for the industrial sector. Ministry of Industry and Information Technology of the People’s Republic of China (MIIT) provided an inventory of key technologies for green transformation and upgrading [13]. These green technologies cover energy-saving and emissions-reduction technologies that need to be fully promoted (such as sintering waste heat recovery, electric furnace dust removal, and energy control centers), key technologies that need to be popularized (such as flue gas waste heat recovery and utilization), and pilot and frontier technologies under research and development. The promotion of low-carbon technologies is an important aspect of reducing emissions in the iron and steel industry in the future. In addition, in this analysis, non-blast furnace ironmaking (DRI and SRI) for replacing blast furnace

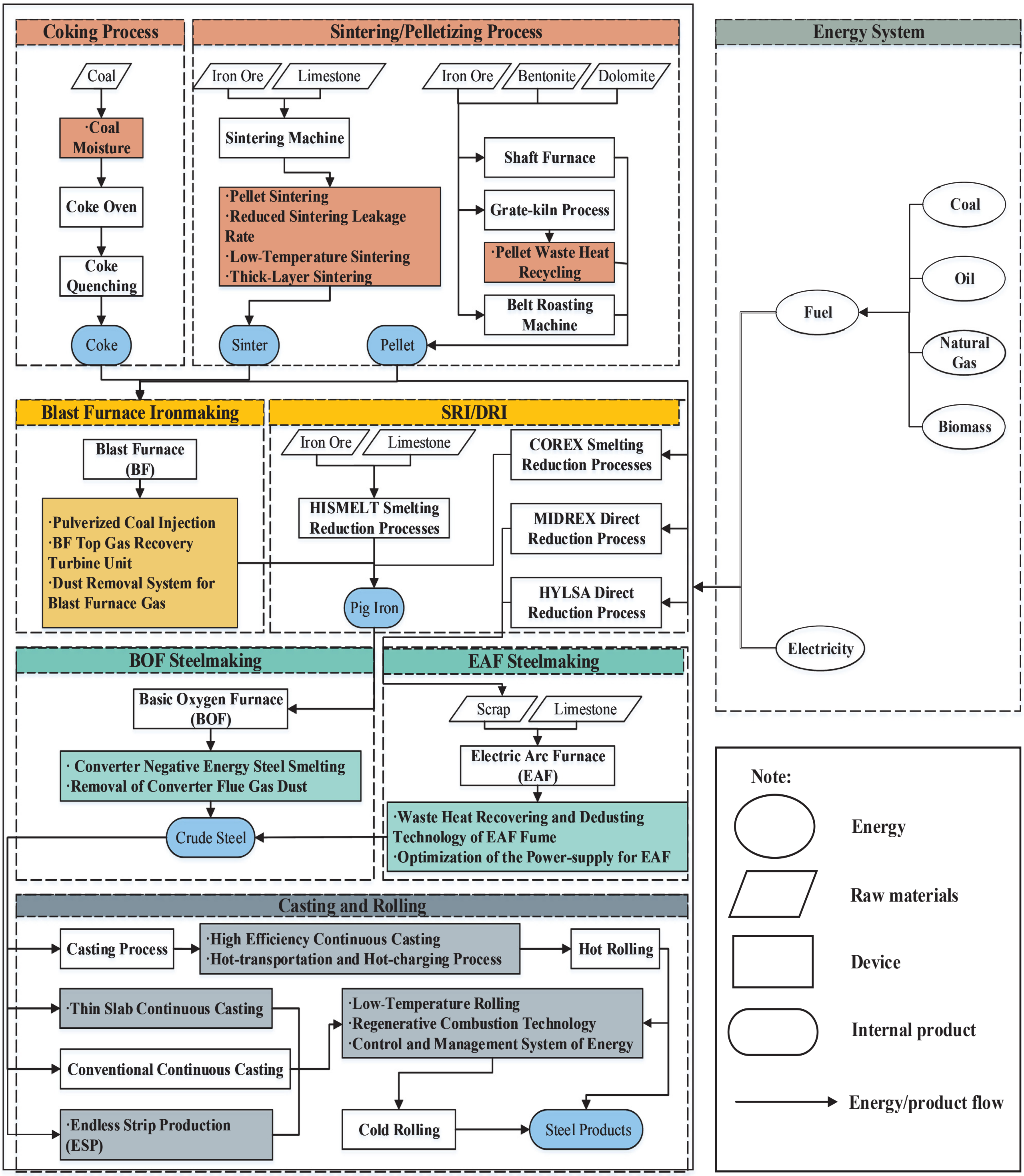

Fig. 3. Structure of China's Iron and Steel Industry in the NET-IS model.

ironmaking technology is also considered for the promotion of low-carbon technologies in the future.

China is accelerating their transition to clean energy. The Chinese government has announced that it is adjusting its energy structure with natural gas reaching 10% in 2020 and non-fossil energy reaching 20% in 2030 [38,39]. This will directly affect the energy structure of the iron and steel industry since it is one of the most energy intensive.

Based on the above major policies and development trends, this paper designs four scenarios, namely, eliminating backward production capacities in accordance with existing major policies (BAU), further adjusting the production structure in addition to BAU (Adjusting the Production Structure [PS]), further promoting low-carbon technology in addition to PS (Promoting Low-carbon Technologies [LT]) and switching to clean fuels in addition to LT (Switching to Clean Fuels [CF]). The differences between the four scenarios are shown in Table 3.

It can be seen that the CF scenario is the combination of the four policies, including phasing out backward production capacity, adjusting the production structure, promoting low-carbon technologies,

Table 2
Main processes and technologies for steel production.

Process	Alternative production technologies (technology substitution and upgrades)	Additional low-carbon technologies (technology retrofitting)
Coking process	Coke oven < 4.3 m Coke oven 4.3–7 m Coke oven > 7 m Advanced coke oven	Coal moisture control Coke dry quenching Coke wet quenching
Sintering process	Sintering machine < 90 m^2 Sintering Machine 90–180 m^2 Sintering machine > 180 m^2 Advanced sintering machine	Pellet sintering Reduced sintering leakage rate Low-temperature sintering technology Thick-layer sintering Sintering waste heat recovery
Pellet process	Shaft furnace Grate-kiln process Belt roasting machine	Pellet waste heat recycling
Blast furnace ironmaking	Blast furnace < 400 m^3 Blast furnace 400–1200 m^3 Blast furnace > 1200 m^3 Advanced blast furnace	Pulverized coal injection Dry BF top gas recovery turbine unit Wet BF top gas recovery turbine unit Dry dust removal system for blast furnace gas Wet dust removal system for blast furnace gas
Non-blast furnace ironmaking	HISMELT smelting reduction process COREX smelting reduction process MIDREX direct reduction process HYLSA direct reduction process	
Basic oxygen furnace (BOF)	Basic oxygen furnace < 30 t Basic oxygen furnace 30–120 t Basic oxygen furnace > 120 t Advanced basic oxygen furnace	Converter negative energy steel smelting Wet removal of converter flue gas dust Dry removal of converter flue gas dust
Electric arc furnace (EAF) steelmaking	EAF < 30 t EAF 30–100 t EAF > 100 t EAF using DRI	Optimization of the power-supply for EAF Waste heat recovering and dedusting technology of EAF fume
Casting and rolling process	Continuously casting machine Advanced continuously casting machine Thin slab continuous casting Conventional continuous casting Endless strip production (ESP) Hot rolling Advanced hot rolling Cold rolling Advanced cold rolling	High-efficiency continuous casting Hot-transportation and hot-charging process Low-temperature rolling Regenerative combustion technology
Whole process		Control and management system of energy

and switching to clean fuels. The scenario setting is based on possible future technological development and energy structures. Considering the uncertainty of future technologies, low-carbon technologies that have not yet appeared on the market are not considered.

4.2. Parameter settings

This study sets 2015 as the base year and 2030 as the target year. The technology portfolio of the steel production process is determined by minimizing the cost and meeting the steel demand of the study year.

Table 3
Scenario descriptions.

Scenario	Description
BAU (Phasing out backward production capacities)	Eliminating backward production capacities and small-scale equipment such as blast furnaces, converters, and EAFs, and increasing the proportion of large-scale and internationally advanced traditional equipment. The new and rebuilt equipment will meet the planning requirements The proportion of EAFs and the share of fossil fuels in BAU will be set according to current trends or evidence from other countries
PS BAU + Adjusting the production structure	On the basis of BAU, the proportion of EAFs will increase in the PS scenario. The average annual growth rate of EAFs will be 13.74% in 2015–2020 and 10.00% in 2020–2030. In 2030, 2/3 of the crude steel will be produced by the BF-BOF process and 1/3 by the EAF process (see Table 4)
LT PS + Promoting low-carbon technologies	On the basis of PS, more low-carbon devices will be added, such as dry-quenching, dry-cleaning, and waste heat recovery. At the same time, non-blast furnace ironmaking will be developed properly
CF LT + Switching to clean fuels	Based on the LT scenario, the energy consumption will shift to more clean fuels following the national energy transition plan. The proportion of coal consumption will be reduced, and the proportion of non-fossil energy and natural gas consumption will be increased significantly (see Table 5)

Table 4
EAF production share in the BAU scenario and lower bounds for annual EAF production share in the PS scenario.

	2015[a]	2020	2030[b]
EAF production share in the BAU scenario (%)	6.10	10.90	23.16
Lower bounds for EAF production share in the PS scenario (%)	6.10	11.61	30.11

[a] Source: Chinese Steel Yearbook 2016 [9] (actual EAF production share).
[b] The changes in the structure of production in 2030 refer to the current world's EAF ratio [40] (future EAF production share).

Table 5
Share of different fuels in the BAU and CF scenarios.

	2015[a]	2020	2030[b]
Upper bound for share of coal in the BAU scenario (%)	93.58	92.1	89.00
Lower bound for share of natural gas in the BAU scenario (%)	1.11	1.73	5.29
Upper bound for share of coal in the CF scenario (%)	93.58	82.89	80.10
Lower bound for share of natural gas in the CF scenario (%)	1.11	1.91	5.82

[a] Source: Chinese Steel Yearbook 2016 [9].
[b] Energy supply ratio in the steel industry is calculated according to the growth rates of China's coal and natural gas consumption [38,39].

By selecting the most economically optimal technology mix, the energy consumption and CO_2 emissions of each technology are calculated, and the total energy consumption and CO_2 emissions of the iron and steel industry can be estimated.

4.2.1. Demand for steel in the future

Here, steel demand refers to production for domestic consumption in China and exports, and the production forecast is based on the results derived from the material flow analysis by Wang et al. [41]. Specifically, the average annual growth rate of steel output is projected to reach 1.85%, −0.67% and −2.27% during 2015–2020, 2020–2025 and 2025–2030, respectively. Driven by infrastructure construction, real estate, the automobile and other sectors, the demand for steel is likely to show slower growth in the near future. This is consistent with the forecast of the results published by the China Metallurgical Industry Planning and Research Institute.[1] After 2020, steel production is expected to show a declining trend because of the overall saturation of steel products and the accelerated policies of phasing out excess capacities. Final steel production values in China used in the NET-IS model are given in Table 6.

4.2.2. Other parameters

Other main parameters used in NET-IS model include technical and energy parameters.

(1) Technical parameters

Technology (equipment) for producing steel includes widely used traditional equipment and advanced low-carbon equipment. Specific technical parameters, including equipment fixed investment costs, operation and maintenance costs, energy input per unit production, and equipment lifetime [42], are collected from the inventory of MIIT [43] and data surveyed from enterprise tender (see Fig. A.1 in Appendix A [44,45]).

Steel equipment lifetime is set following the Weibull distribution, which it is widely used for simulating the life-span of equipment. It is assumed that the shape parameter in the Weibull distribution function is 1 [46].

[1] http://www.steelplanning.cn/xwzx/tpxw_449/201712/t20171204_73374.html (in Chinese).

Table 6
Steel production in China during 2015–2030.

	2015	2016	2017	2018	2019	2020	2025	2030
Steel production (million tons)	803.8	818.7	833.9	849.3	865.1	881.1	852.1	759.6

Table 7
Emission factors of fuels in China's iron and steel sector.

	Raw coal	Fuel oil	Natural gas	Coking coal
Emission factor (tCO_2/tce)	2.6604	2.1526	1.6278	2.3547

(2) Energy parameters

This paper assumes that the emission factors for various energy sources will remain constant during 2015–2030, as shown in Table 7 [47]. The conversion factors from physical units to coal equivalent values come from the National Bureau of Statistics of the People's Republic of China (NBS/PRC) [48], and the electricity emission factor is derived from the results of NET-Power model, as shown in Table 8, which considers the fuel structure change of power generation during 2015–2030. The energy prices data comes from the Wind database,[2] and the price changes in the coming years are assumed following the rate of price change given by the Energy Information Administration (EIA) [49].

5. Results and discussion

Based on the estimation of NET-IS model under four scenarios, we introduce the results related to the potential of CO_2 emission reduction and energy savings in the iron and steel industry in China, as well as the corresponding total and unit abatement costs.

5.1. Potential of CO_2 emission reduction

During 2015–2019, the CO_2 emissions in the BAU scenario are likely to increase from 1352.21 million tonnes of CO_2 ($MtCO_2$) to 1390.11 $MtCO_2$, with an annual growth rate of 0.69%. CO_2 emissions may peak in 2019 under the BAU scenario. After 2020, small and backward production equipment will be phased out and newly-recruited production equipment should meet the entry criteria. As the production equipment becomes more large-scale and advanced, CO_2 emissions will decrease rapidly. CO_2 emissions could drop to 999.89 $MtCO_2$ by 2030, a reduction of 352.32 $MtCO_2$ compared with 2015.

As shown in Fig. 4, similar trends with decreasing CO_2 emissions can be revealed in the other three scenarios that introduce more severe mitigation strategies in addition to the BAU. Compared with the BAU, an accelerated shift of the production process to EAF in the PS scenario can reduce CO_2 emissions by 142.02 $MtCO_2$ in total during 2015–2030, and the CO_2 emissions would be 985.43 $MtCO_2$ in 2030. After introducing more low-carbon technologies (LT scenario), the potential of CO_2 emission reduction would be intensified, along with cumulative CO_2 emission reduction reaching up to 585.22 $MtCO_2$ during 2015–2030, compared with the PS scenario. Further shifting to the use of clean energy in the CF scenario could bring a total of 89.07 $MtCO_2$ emission reduction during 2015–2030 compared with the LT scenario. Consequently, with the above three strategies, the potential of CO_2 emission reduction in the iron and steel industry in China until 2030 could reach 818.30 $MtCO_2$.

Fig. 5. shows CO_2 emissions for the four scenarios in 2020 and 2030.

[2] http://www.wind.com.cn/newsite/edb.html.

Table 8
Emission factors of electricity in China's iron and steel sector.

	2015	2020	2025	2030
Emission factor (tCO_2/tce)	2.6216	2.9023	2.8386	2.8566

Source: The results of NET–Power model.

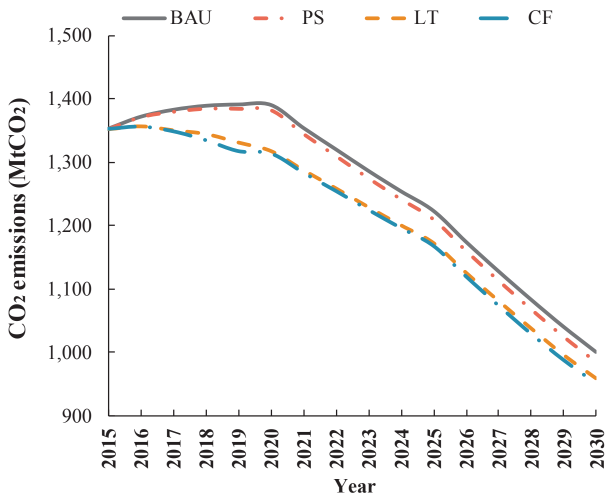

Fig. 4. CO_2 emissions in China's iron and steel industry.

In 2030, as the proportion of EAF increases from 23.16% in the BAU to 30.11% in the PS scenario, CO_2 emissions will decrease by 0.54% and 1.45% in 2020 and 2030, respectively, in the PS compared with the BAU scenario. It can be seen that, under current conditions, the potential of CO_2 emission reduction is very limited if only relying on the transition of the production process to EAF. In 2020 and 2030, the share of coal consumption in the CF scenario is 82.89% and 80.10%, respectively, much lower than the share in the LT scenario (92.10% and 89.00%, respectively). This leads to 4.31 Mt and 7.06 Mt of CO_2 emission reduction in 2020 and 2030, respectively. Compared with the PS scenario, the development of low-carbon technologies could lead to 64.11 Mt (4.64%) and 26.84 Mt (2.72%) of CO_2 emission reduction in 2020 and 2030. respectively. In contrast to increasing the number of EAFs and shifting to clean fuels, the CO_2 emission reduction brought by the promotion of low-carbon technologies is the most evident. Therefore, it is necessary to install improved devices and optimize technology deployment during the production process.

5.2. Total and unit abatement costs of CO_2 emission reduction

When we assess the mitigation potential of the iron and steel industry, the corresponding cost must be taken into account. Fig. 6 shows the cost differences between the four scenarios. In the PS scenario with a higher proportion of EAFs, the cumulative investment costs would increase by 692.59 billion CNY during 2015–2030 compared with the existing policy scenario (BAU) because the scrap prices and operating costs of EAFs are much more expensive. In addition, current technologies widely used in China's iron and steel industry are relatively backward. The adoption of low-carbon technologies in the LT scenario implies higher costs. It is estimated that the total cost in the LT scenario during 2015–2030 would be approximately 475.69 billion CNY more than that in the BAU scenario. However, the cost in the LT scenario is 216.90 billion CNY less than that in the PS scenario, demonstrating the economic benefits of developing low-carbon technologies. Therein, the coke dry quenching technology, sintering waste heat recovery, dry BF top gas recovery turbine unit, and optimization of the power-supply for EAF make the greatest contributions to energy cost savings compared with the PS scenario. Furthermore, the cost reduction caused by energy savings during 2015–2030 is greater than the additional investment and operating costs, owing to the introduction of these new technologies. In the CF scenario, clean energy always has a higher market price relative to traditional coal. Hence, limiting the proportion of coal consumption will increase energy costs. Whereas, since EAF production processes can omit coking, sintering, and blast furnace ironmaking processes, and the application of new technologies can increase production efficiency, energy consumption per unit of steel products may be reduced, thereby saving energy costs. The cumulative costs increase by 661.04 billion CNY in the CF scenario compared with the BAU scenario and by 185.35 billion CNY compared with the LT scenario during 2015–2030. Comparing these three scenarios, it is not difficult to see that the shift from converters to EAFs in the PS scenario would have the greatest impact on the cost of CO_2 emission reduction.

Based on the total costs and CO_2 emissions mentioned above in the four scenarios, the unit abatement cost of CO_2 emission reduction in PS, LT, and CF are calculated by regarding BAU as the reference (see Fig. 7). Further increasing the proportion of EAFs in addition to the BAU would result in the unit abatement cost of CO_2 emission reduction being 3950 CNY/tCO_2 in 2020, 4770 CNY/tCO_2 in 2025, and 6050 CNY/tCO_2 in 2030. With additional measures for developing low-carbon technologies in the LT scenario, the unit abatement cost would drop substantially to 140 CNY/tCO_2, 870 CNY/tCO_2 and 1680 CNY/tCO_2 in 2020, 2025, and 2030, respectively. Compared with the LT scenario, shifting to more clean energy production (CF) is likely to increase the unit abatement costs to approximately 300 CNY/tCO_2, 1070 CNY/tCO_2, and 1740 CNY/tCO_2 in 2020, 2025, and 2030, respectively.

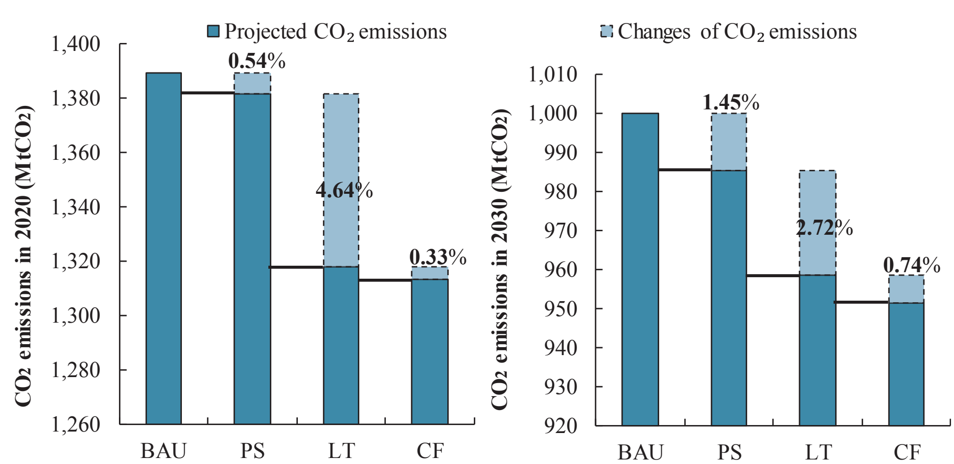

Fig. 5. CO_2 emissions in China's iron and steel industry in 2020 (left) and 2030 (right).

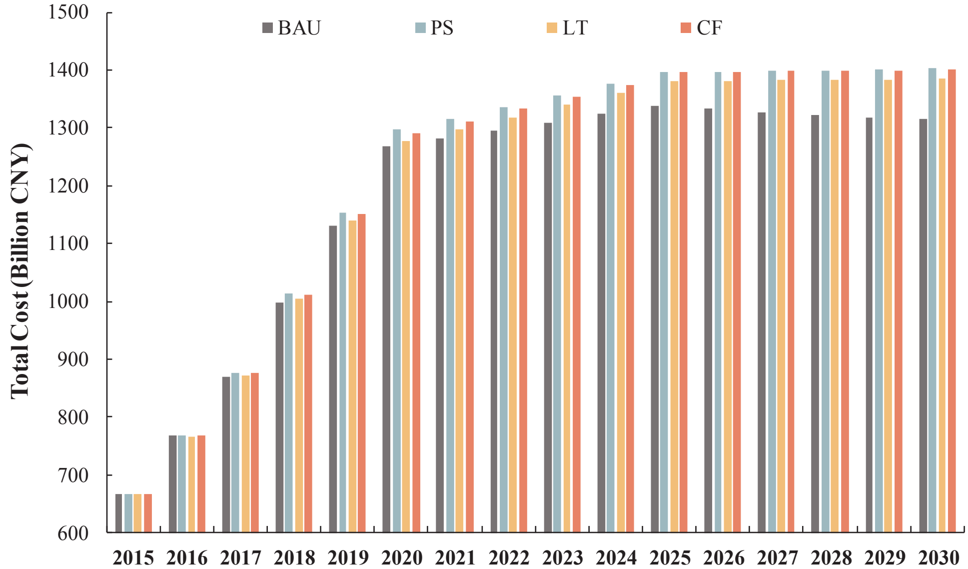

Fig. 6. Production cost in China's iron and steel industry during 2015–2030.

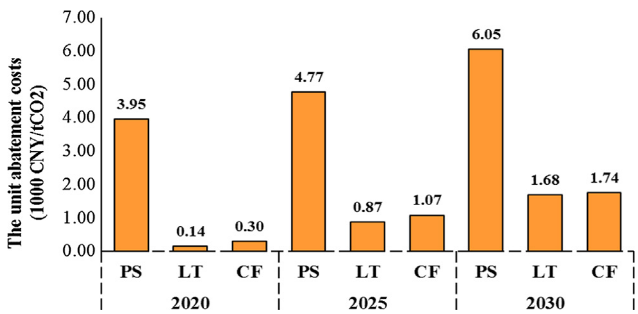

Fig. 7. The unit abatement costs of CO_2 emission reduction under different scenarios in China's iron and steel industry.

It can be seen that the development of low-carbon technologies can significantly reduce the unit abatement costs of emission reduction, but with an increasing trend of unit abatement costs. Therefore, to offset the cost increments, achieving the large-scale production and popularization of low-carbon technologies (i.e., the LT scenario) is key to reducing the abatement costs and increasing the potential of CO_2 emission reduction.

5.3. Potential of energy savings

Fig. 8. shows annual energy consumption in the four scenarios and the annual steel production. It can be seen that from 2015 to 2030, the iron and steel industry in China would need 8221.21 million ton coal equivalent (Mtce) of energy consumption in total if following the current policies. After introducing feasible mitigation interventions, including further increasing EAFs, low-carbon technologies and clean fuels, the potential of energy savings could achieve 321.35 Mtce, or around 4.2% of total increasing energy.

Before 2018, energy consumption shows a slight increase in the BAU scenario because of increased steel production. During 2020–2030, declining steel production and the effective implementation of the policy of eliminating backward production capacities (e.g., large-scale equipment gradually replaces small-scale and backward production equipment) would result in energy consumption decreasing year by year in the BAU scenario. In addition, accelerating the promotion of advanced low-carbon technologies could help save energy. Specifically, compared with the BAU scenario, an increase of in the EAF ratio could reduce energy consumption by 68.42 Mtce during 2015–2030. Compared with the PS scenario, further promoting low-carbon technologies in the LT scenario could reduce energy consumption by 241.92 Mtce. However, the energy-saving potential of switching to clean energy is limited, with only 11.01 Mtce of energy savings in the CF compared with the LT scenario during 2015–2030.

Fig. 9 shows the energy consumption of the four scenarios in 2020 and 2030, and the energy-saving ratios relative to the former scenarios are given. Comparing the energy-saving ratios of different scenarios, we can see that the development of low-carbon technologies in the LT scenario would have the greatest energy-saving potential. Compared with the PS scenario, in 2020 and 2030, the development of low-carbon technologies would result in energy savings of 25.25 Mtce and 12.30 Mtce, respectively, and energy consumption would be reduced by 4.50% and 3.07%, respectively. In 2020 and 2030, energy consumption in the PS scenario would be reduced by 0.65% and 1.73%, respectively, compared with that in the BAU scenario. It can be seen that the transition of the production process makes a limited contribution to energy savings. Compared with the LT scenario, the CF scenario could bring energy savings of 0.23 Mtce and 7.06 Mtce in 2020 and 2030, respectively. Switching to clean fuels would make the smallest contribution to energy savings compared with other scenarios. Therefore, in the future, for the promotion of energy-saving policies in the iron and steel industry, we should give priority to the development of low-carbon technologies.

5.4. Structure of energy sources

Fig. 10 shows the structure of energy consumption (including electricity) under the BAU and three alternative scenarios for China's iron and steel industry. In the PS, LT, and CF scenarios, the share of electricity among energy sources would increase during the study period. In the PS scenario, the increase in the share of EAF production would shift energy consumption from coal to electricity. In 2030, the share of electricity would be 48.24% in the BAU scenario, while it would increase to 51.42% in the PS scenario. The development of low-carbon technologies, mainly including the promotion of various waste heat power generation and power optimization technologies, would result in more electricity savings compared with the reductions of coal and other types of fuel consumption. Accordingly, the share of electricity would go down, and the share of coal consumption would rise in 2030 relative to 2020 and the BAU values. Switching to clean fuels is the most intuitive way to change the energy structure. Under the CF

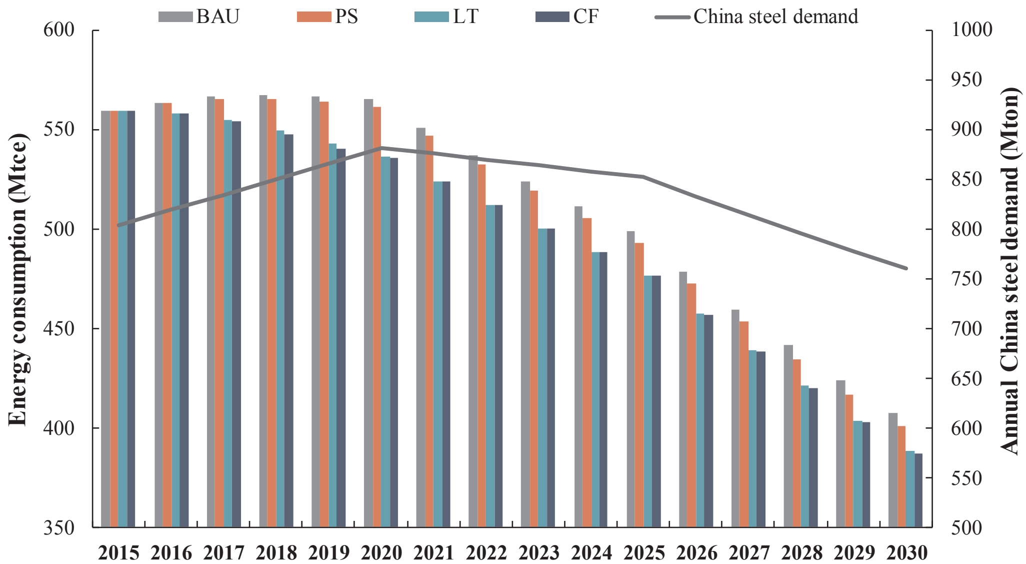

Fig. 8. Energy consumption in different scenarios (including coke consumption) during 2015–2030.

scenario, the proportion of coal consumption would decrease by 2.82% compared with the BAU scenario in 2030. As can be seen in Fig. 10, although the restrictions on coal consumption are strengthened and the use of natural gas is increased, the market would not choose natural gas as the fuel for steel production because of cost constraints. Therefore, the state or government is suggested to continue supporting policies for natural gas so as to fulfill the target of energy transition in the iron and steel industry in China.

5.5. Energy consumption by different technologies

To investigate where the above energy savings originated, Fig. 11 further shows the energy consumption (excluding coke consumption) contributed by different technologies in the CF compared with the BAU scenario. We can see that traditional production technologies (hot rolling, large blast furnaces, middle coke ovens, etc.) would bring the most significant energy savings, at about 137.28 Mtce, or 44.97% of the total energy savings. The technology penetration rates of these three technologies in 2030 are up to 22.14%, 98.53%, and 91.57%, respectively. The use of thin slab continuous casting technology as an alternative to replace traditional hot rolling would play a significant role in energy savings. Compared with the BAU scenario, the energy consumption of thin slab continuous casting technology in the CF scenario would increase by 23.46 Mtce during 2015–2030, while that of the hot rolling process would decrease by 54.95 Mtce, which accounts for 18.00% of the total energy savings. The non-blast furnace would replace part of the blast furnace ironmaking in the future. Compared with the BAU scenario, the energy consumption of the Hismelt and Corex smelting reduction technologies would increase by 11.45 Mtce and 136.51 Mtce, respectively, in the CF scenario during 2015–2030, for which the penetration rates would reach 3.81% and 9.64%, respectively, among ironmaking technologies. DRI technology may not start to be popularized during this period. The medium and large EAFs would rapidly replace BOFs, whose technology penetration rates in 2030 would be up to 46.17% and 58.83%, respectively; this would make a major contribution to the energy savings. During 2015–2030, compared with the BAU scenario, the total energy consumption of medium and large EAFs would increase by 56.81 Mtce. However, owing to the replacement of traditional coal-dominant BF-BOFs by the EAFs, the energy structure would be cleaner, and the share of coal would decrease by 11.55% compared with the BAU scenario in 2030.

The development of additional low-carbon technologies is also very important for energy savings. Regenerative combustion and pulverized coal injection technologies would become widely used for rolling process and blast furnace ironmaking in the future (100% in 2030), and these would become the largest contributor to energy savings in the CF scenario (16.4%), which is 50.08 Mtce of energy less consumed during 2015–2030. Regenerative combustion technology making use of low

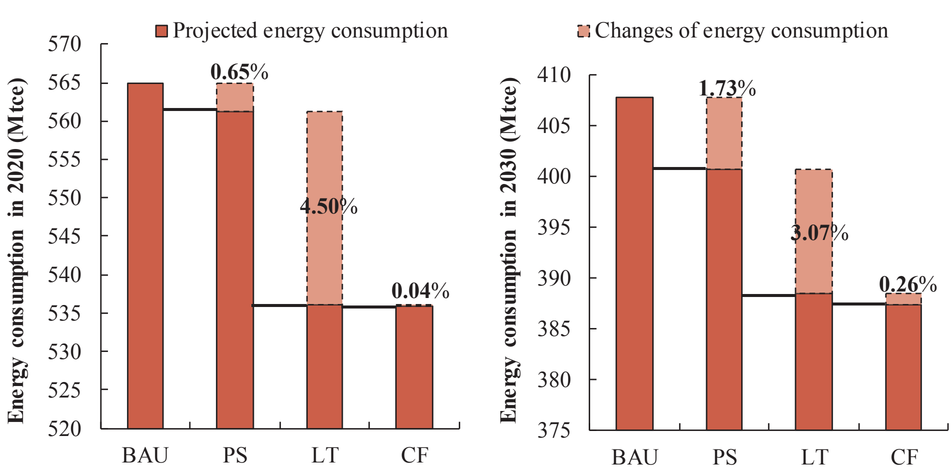

Fig. 9. Energy consumption in China's iron and steel industry in 2020 (left) and 2030 (right).

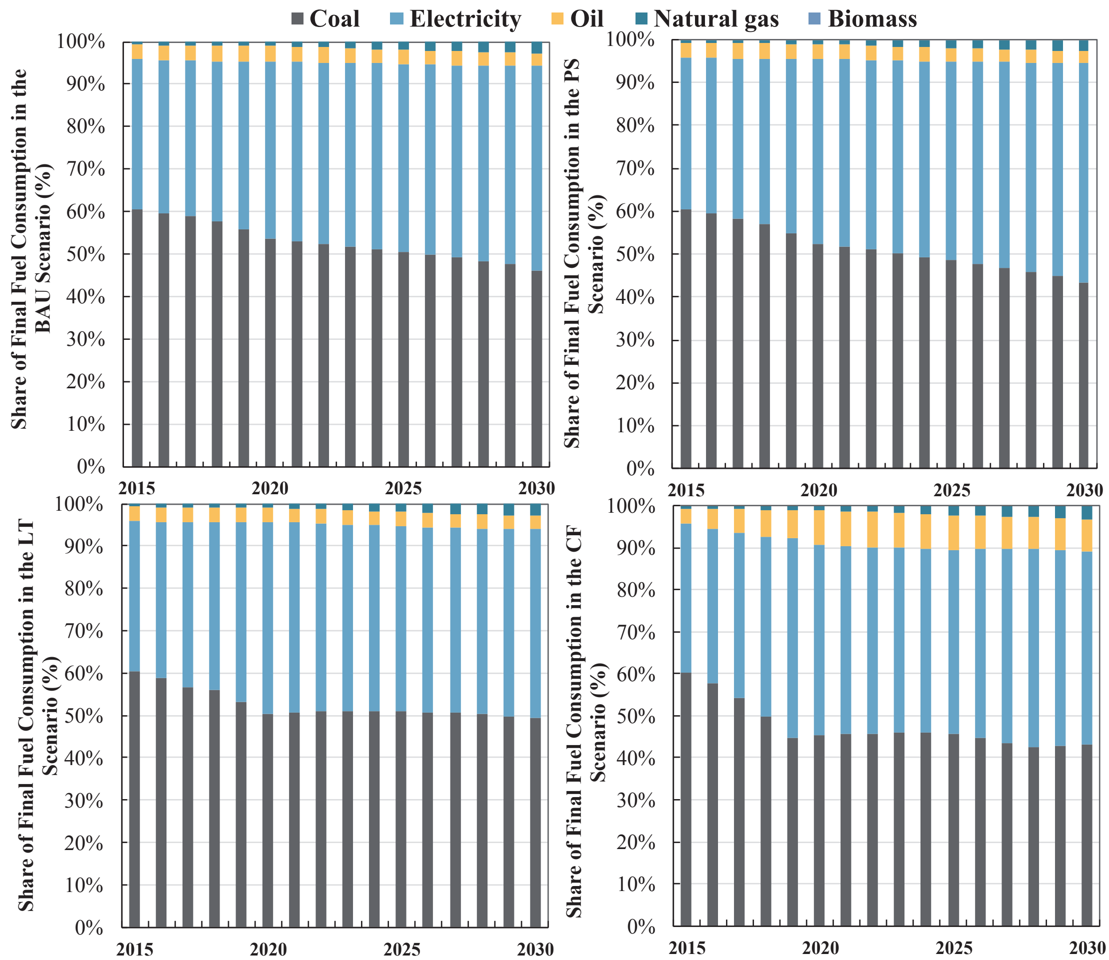

Fig. 10. Structure of energy sources in the iron and steel industry in China.

calorific value fuels (such as blast furnace gas) helps reduce pollutants (blast furnace gas) and energy. Blast furnace pulverized coal injection can use a variety of coal species and ease the shortage of coking coal in China. At the same time, with the large difference between coke and coal prices, using blast furnace pulverized coal injection can reduce not only coke and energy consumption, but also pig iron production costs. Meanwhile, the use of a series of additional low-carbon technologies, such as coke dry quenching and coal moisture control, would be increased. Thus, adjusting the production structure, promoting low-carbon technologies, and switching to clean fuels would enhance the use of large-scale equipment and low-carbon technologies.

5.6. Development path for low-carbon technologies

To achieve the potential energy savings and CO_2 emission reduction, the corresponding development paths for low-carbon technologies are displayed in Fig. 12. Here we only target the CF scenario. As can be seen, each technology has different promoting rates at different periods. From 2015 to 2020, a series of technologies, including a dry dust removal system for blast furnace gas and high-efficiency continuous casting, would grow slowly at average annual growth rates of 2.46% and 1.67%, respectively. Under current cost-optimizing goals, the development of these technologies would be limited.

At the same time, pellet sintering, reduced sintering leakage rate, low-temperature sintering technology, and thick-layer sintering would reach saturation in 2020. Furthermore, HISMELT smelting reduction process, direct reduction ironmaking, sintering waste heat recovery, grate-kiln process, and endless strip production (ESP) would not be the prior low-carbon technologies during 2015–2030. In China's iron and steel industry, there is limited room for developing DRI. The development of non-blast furnace ironmaking is still subject to cost constraints in the future. Because of the reality of the coal-dominant resource endowments in China, coal prices are still low compared with other energy sources, which maintains blast furnace ironmaking as the main process of ironmaking in China's iron and steel industry.

6. Conclusions and policy implications

6.1. Conclusions

In targeting the iron and steel industry, this paper examines the impact of the following four mainstream policy strategies on energy savings and CO_2 emission reduction: eliminating backward production capacities, adjusting production structures, promoting low-carbon technologies, and switching to clean fuels. To that end, we established a bottom-up cost-minimization model called the NET model. Our results show that the involved policies can achieve different levels of energy savings and emission reduction. However, how much mitigation potential can be achieved will be limited by the level of technical efficiency and corresponding costs. More specifically:

(1) The existing policy of phasing out backward production capacities would contribute greatly to energy savings and CO_2 emission reduction in China's iron and steel industry. Energy consumption and CO_2 emissions would be reduced by 26.06% and 27.11%, respectively, in 2030 compared with 2015. At the same time, the iron and

Fig. 11. Energy savings contributed by each technology in China's iron and steel industry in the CF compared with BAU scenario (excluding coke consumption). Note: Positive values mean energy savings, and negative values mean energy increments. Contribution to energy savings (%) indicates the percentage of energy savings of each technology in the total energy savings, not including energy increments.

steel industry would continue to have enormous energy consumption and CO_2 emissions. Cumulative energy consumption would reach 8.2 Gtce (billion tce) and cumulative CO_2 emissions would be 20.13 $GtCO_2$ (billion tonnes of CO_2) during 2015–2030.

(2) Before 2030, reducing energy consumption and CO_2 emissions would rely heavily on improving energy efficiency by promoting the deployment of low-carbon technologies (LT), which could contribute 587.2 $MtCO_2$ of emission reduction during 2015–2030 compared with the PS scenario (structural changes to promote EAFs). Structural changes to promote EAFs (PS) would be very important in the long run. Switching to clean fuels (CF) would not become the preferred policy for low-carbon development in China's iron and steel industry because it would decrease CO_2 emissions by 89.07 $MtCO_2$ compared with the LT scenario.

(3) Promoting low-carbon technologies could significantly reduce the abatement cost of CO_2 emissions, which would reduce the cumulative cost by 216.90 billion CNY compared with the PS scenario during 2015–2030. By contrast, the additional implementation of promoting EAFs in the PS scenario and switching to clean fuels in the CF scenario would cause an increase in total costs. Therefore, promoting low-carbon technologies could provide some economic benefits.

(4) In the future, blast furnace ironmaking could still be the main process of ironmaking. The development of sintering waste heat recovery, grate-kiln process and ESP technology would be constrained by their high investment costs.

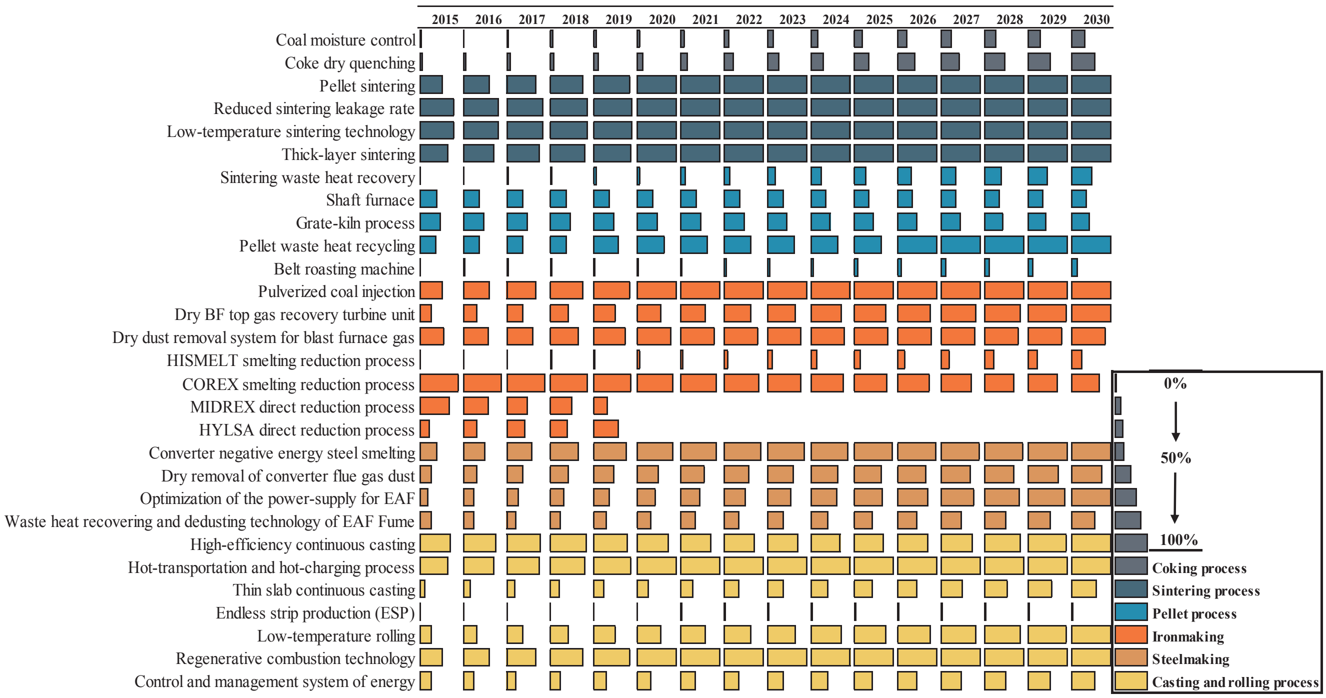

Fig. 12. Promotion rates of advanced technologies for selected years under the CF scenario.

6.2. Policy implications

Based on the analysis and discussions of the results, this paper proposes the following two suggestions:

(1) Fewer carbon allowances and tighter carbon emissions caps are required for China's iron and steel industry. In 2016, the average carbon price in various carbon trading pilot projects was lower than 53.6 CNY/ton in China. According to our findings, the unit abatement costs in the iron and steel industry would be about 300 CNY/ton in 2020 and 1740 CNY/ton in 2030, much higher than the current carbon prices. To promote CO_2 emission reduction, it is proposed to set fewer carbon allowances and tighter the carbon emissions cap in the iron and steel industry. On the other hand, because low-carbon technologies are found to contribute substantially to lowering the unit abatement costs, enterprises are encouraged to develop independent technological innovations to make up for the cost loss caused by carbon trading.

(2) During 2015–2020, low-carbon technologies such as low-temperature sintering and reduced sintering leakage rate will play an important role in reducing CO_2 emissions in China's iron and steel industry. During 2020–2030, the development of these low-carbon technologies would be saturated, and optimization of the power-supply for EAF and the removal of converter flue gas dust would lead to greater CO_2 emission reduction. The development of technologies such as non-blast furnace ironmaking, ESP technology, dry dust removal system for blast furnace gas, and waste heat recovering and dedusting technology of EAF fume is hindered in China because of their high costs. To achieve greater CO_2 emission reduction, the Chinese government should consider subsidizing these high-cost yet highly efficient technologies.

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Appendix A

Here, we briefly explain the industrial process for iron and steel making and the main technologies used in each process (MIIT, 2012) (see Tables A.1 and A.2).

Table A.1
Upper bounds of different low-carbon technologies in the PS and LT scenarios.

No.	Technology	PS (%)			LT (%)		
		2015	2020	2030	2015	2020	2030
1	Fuel Mix, Coal	93.58	92.1	89	93.58	92.1	89
2	Fuel Mix, Oil	5.31	100	100	5.31	100	100
3	Fuel Mix, Natural Gas	1.11	100	100	1.11	100	100
4	Fuel Mix, Biomass	0	100	100	0	100	100
5	Coke oven < 4.3 m	5	0	0	5	0	0
6	Coke oven 4.3–7 m	88.61	100	100	88.61	100	100

(continued on next page)

Table A.1 (*continued*)

No.	Technology	PS (%)			LT (%)		
		2015	2020	2030	2015	2020	2030
7	Coke oven > 7 m	4.39	6.43	16.67	4.39	6.43	16.67
8	Advanced coke oven	2	2.93	7.59	2	2.93	7.59
9	Coal moisture control	4.39	6.43	16.68	4.39	9.18	37.13
10	Coke dry quenching	7.32	10.72	27.8	7.32	15.3	61.88
11	Coke wet quenching	92.68	100	100	92.68	100	100
12	Sintering machine < 90 m^2	0	0	0	0	0	0
13	Sintering Machine 90–180 m^2	26.2	100	100	26.2	100	100
14	Sintering machine > 180 m^2	71.8	74.71	82.53	71.8	74.71	82.53
15	Advanced sintering machine	2	2.93	7.59	2	2.93	7.59
16	Pellet sintering	58.56	85.74	100	58.56	100	100
17	Reduced sintering leakage rate	87	100	100	87	100	100
18	Low-temperature sintering technology	87	100	100	87	100	100
19	Thick-layer sintering	72.84	75.79	100	72.84	100	100
20	Sintering waste heat recovery	2.93	4.29	26.54	2.93	8.6	53.25
21	Shaft furnace	43.24	41.56	37.62	43.24	41.56	37.62
22	Grate-kiln process	100	100	100	100	100	100
23	Pellet waste heat recycling	21.85	22.74	25.12	21.85	53.78	87.59
24	Belt roasting machine	4.01	5.91	15.33	4.01	5.91	15.33
25	Blast furnace < 400 m^3	0	0	0	0	0	0
26	Blast furnace 400–1200 m^3	26.2	100	100	26.2	100	100
27	Blast furnace > 1200 m^3	71.8	74.71	100	71.8	74.71	100
28	Advanced blast furnace	2	2.93	7.59	2	2.93	7.59
29	Pulverized coal injection	58.56	85.74	100	58.56	100	100
30	Dry BF top gas recovery turbine unit	29.28	42.87	100	29.28	61.18	100
31	Wet BF top gas recovery turbine unit	70.72	80	80	70.72	80	80
32	Dry dust removal system for blast furnace gas	60.78	73.87	100	60.78	100	100
33	Wet dust removal system for blast furnace gas	39.22	50	50	39.22	50	50
34	HISMELT smelting reduction process	2	2.93	7.59	2	7	28.3
35	COREX smelting reduction process	98	100	100	98	100	100
36	MIDREX direct reduction process	73.98	75	75	73.98	75	75
37	HYLSA direct reduction process	26.02	27.07	29.9	26.02	76.48	100
38	Basic oxygen furnace < 30 t	0	0	0	0	0	0
39	Basic oxygen furnace 30–120 t	44.93	100	100	44.93	100	100
40	Basic oxygen furnace > 120 t	53.07	55.23	61	53.07	55.23	61
41	Advanced basic oxygen furnace	2	2.93	7.59	2	2.93	7.59
42	Converter negative energy steel smelting	45.39	66.45	100	45.39	91.77	100
43	Wet removal of converter flue gas dust	29.28	42.87	100	29.28	61.18	100
44	Dry removal of converter flue gas dust	70.72	80	80	70.72	80	80
45	EAF < 30 t	0	0	0	0	0	0
46	EAF 30–100 t	53.17	100	100	53.17	100	100
47	EAF > 100 t	46.83	48.73	53.83	46.83	48.73	53.83
48	Optimization of the power-supply for EAF	21.96	32.15	83.4	21.96	45.89	100
49	Waste heat recovering and dedusting technology of EAF fume	29.28	42.87	100	29.28	61.18	100
50	EAF using DRI	2	2.93	7.59	2	5.35	15
51	Continuously casting machine	98	100	100	98	100	100
52	Advanced continuously casting machine	2	2.93	7.59	2	2.93	7.59
53	High-efficiency continuous casting	78.05	81.27	92.11	78.05	100	100
54	Hot-transportation and hot-charging process	72.84	75.8	83.73	72.84	100	100
55	Thin slab continuous casting	15	32.15	83.4	15	64.5	100
56	Conventional continuous casting	24	85	85	24	85	85
57	Endless strip production (ESP)	4	5.86	15.19	4	12.44	20.27
58	Hot rolling	55	100	100	55	100	100
59	Advanced hot rolling	2	2.93	7.59	2	2.93	7.59
60	Low-temperature rolling	29.28	42.87	100	29.28	61.18	100
61	Regenerative combustion technology	58.56	85.74	100	58.56	100	100
62	Cold rolling	98	100	100	98	100	100
63	Advanced cold rolling	2	2.93	7.59	2	2.93	7.59
64	Control and management system of energy	29.28	42.87	100	29.28	61.18	100

Table A.2
Other parameters of the NET-IS model.

Item	Value	Ref.
r	12%	[48]
$\eta_{t,1}$	10%	[49]
$\varepsilon_{t,1}$	2%	[48]

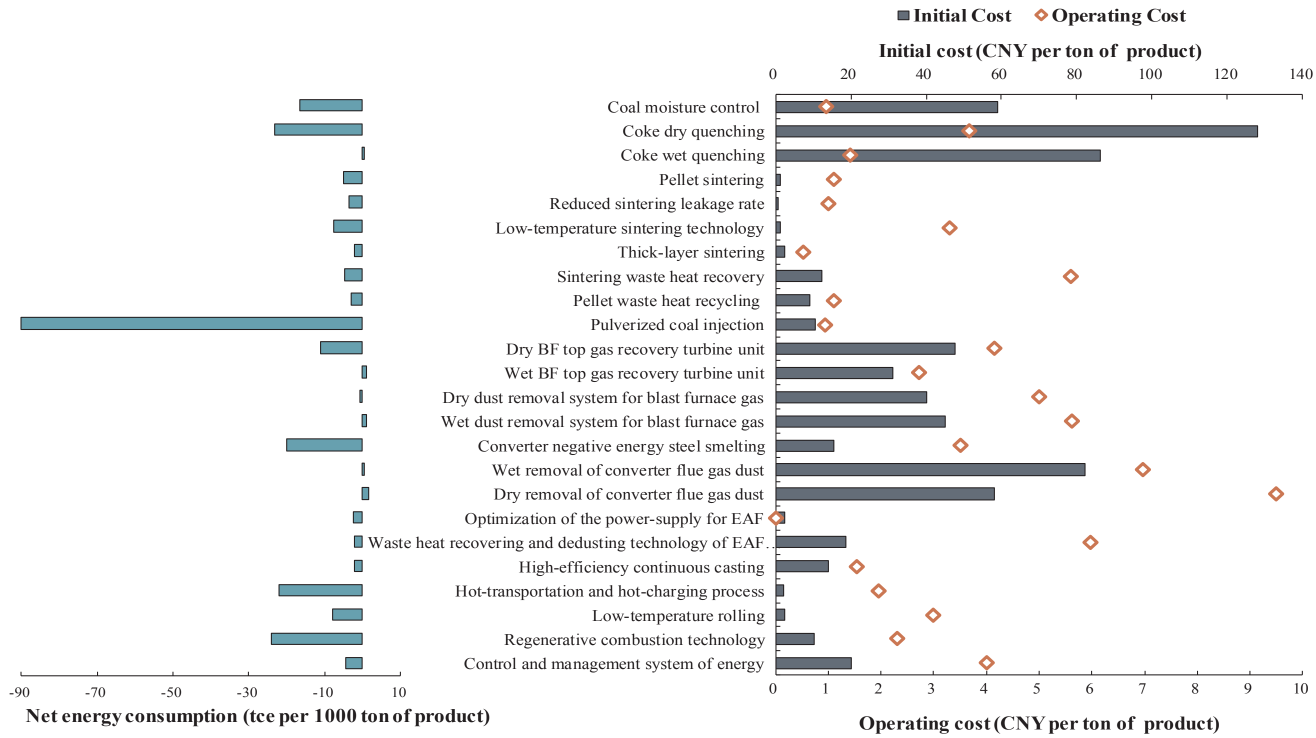

Fig. A.1. Basic parameters of energy consumption and costs for low-carbon devices in China's iron and steel industry.
Source: The equipment initial cost and operating cost is from [43].

(1) ***Coking process:***

Coking refers to the process of heating the coking coal to about 1000 °C (high temperature carbonization) without the air and producing coke oven gas and other coking chemical products through the thermal decomposition and coking.

The main equipment for coking includes large, medium and small coke ovens according to the height of carbonization chamber. There are different energy-saving devices can further be installed adhere to the coke oven, including:

Coal moisture control: a technology for removing part of the water before putting coking coal into the furnace so that the percentage of water in the coal can be controlled at about 6%.

Coke quenching: coke quenching includes **Wet quenching** and **Dry quenching** methods. Wet quenching carries the red-hot coke to the quenching coke tower, and sprays the coke with high pressure water. Dry quenching puts the red hot coke into the quenching room and recycle the physical heat of coke with inert gas.

(2) ***Sintering/Pellet process:***

In order to improve the utilization rate of raw materials in the blast furnace, artificial lump ore needs to be made. At present, the artificial lump ore in the world is mainly produced by sintering method and the pellet method. Iron ore can be processed at sintering plants and pelletizing plants for sinter and pellet.

Sintering plant is divided into large, medium and small sintering plants according to the sintering area. There are different energy-saving devices can further be installed with the sintering plant, such as:

Technology for pellet sintering: the pellet sintering can improve the permeability of the sintered mixture, thereby increase the yield and quality of sinter.

Reduced sintering leakage rate: a technology for reducing the air leakage of the exhaust fan thus reducing the power consumption.

Low-temperature sintering technology: Under the condition of low sintering temperature (1200 °C), the oxidizing atmosphere is developed to promote the solid phase reaction. The sinter is formed with low-temperature slender calcium ferrite as the main binder phase, and the other minerals are bonded to form interweave multiphase structure of the production process, with significant energy savings and improvement of sinter performance.

Thick-layer sintering: By increasing the sintering machine trolley fence and the thickness of material layer, the automatic heat storage material layer is used to reduce the carbon content in the mixture and develop the oxidizing atmosphere in the sintering layer, which can reduce the solid fuel consumption and improve the sinter quality.

Sintering waste heat recovery: a technology for recycling the heat of exhaust gas generated in the sintering process and can be used for heating and power generation.

Pelletizing, similar to sintering, is a processing method of providing "sugar" for the blast furnace. It is a process that makes finely ground concentrate or powdered material to produce the raw material that can meet the requirements of blast furnace smelting.

At present, the main types of pellets roasting method include: **Shaft furnace**, **Belt roasting machine**, **Grate-kiln process**. Shaft furnace is the earliest, but it develops slowly because of its inherent shortcomings. At present, the most commonly used is the belt roasting machine with more than 60% of penetration rate. Grate-kiln process appears late, but it is likely to become the dominant pellet roaster method in the future.

Grate-kiln process can be installed with **pellet waste heat recycling** technology, which is for reusing or recycling the waste heat generated by cooling and roasting.

(3) ***Blast furnace ironmaking:***

Blast furnace ironmaking process requires the input of sinter/pellet, coke and limestone to the blast furnace equipment. At high temperature, iron ore smelts pig iron through the reduction reaction, and hot metal is released from the tap hole.

According to the volume of equipment, blast furnace can be divided into large, medium and small blast furnace. Blast furnace can further be installed with energy-saving equipment, including:

Pulverized coal injection: a technology for blasting the pulverized anthracite, bituminous coal or a mixture of pulverized coal and bituminous coal.

Dry BF top gas recovery turbine unit (TRT): a technology for introducing the gas into a turbine expander to convert pressure energy and heat into mechanical energy and drive generator to produce electricity.

Dust removal system for blast furnace gas: It can be divided into **wet dust removal** and **dry dust removal**. When the content of blast furnace gas dust exceeds $10\,mg/m^3$, it will be harmful to the gas system. Therefore, it is necessary to consider the purification and dedusting of the gas.

(4) ***Non-blast furnace ironmaking:***

Non-blast furnace ironmaking means ironmaking outside the blast furnace, mainly including direct reduction ironmaking and smelting reduction ironmaking.

Direct reduction ironmaking (DRI): a technology reduces the refined iron powder or iron oxide to the low carbon porous material at a low temperature, mainly including **MIDREX direct reduction process** and **HYLSA direct reduction process**.

Smelting reduction ironmaking (SRI): a technology uses reductant to reduce the iron oxide in the molten state to metal iron, mainly including the COREX smelting reduction process and the HISMELT smelting reduction process. The COREX smelting reduction process is the only SRI technology that has been put into practice besides the blast furnace. The HISMELT smelting reduction process is still under the industrial experiment stage.

(5) ***Basic oxygen furnace (BOF)/Converter steelmaking:***

BOF uses oxygen to react in molten iron, reduce impurities and produce steel. When the content of carbon dropped below 2%, it can become steel. BOF can be divided into large, medium and small sized furnace according to capacity. The BOF equipment can be installed with energy-saving devices, including:

Converter negative energy steel smelting: a combination of technologies that can increase the rate of utilization and recycling of converter gas and converter smoke waste heat.

Technology for removal of converter flue gas: technology for purifying furnace gas, which includes **wet removal of converter flue gas dust** and **dry removal of converter flue gas dust**. **Wet removal of converter flue gas dust** is to transfer the dust particles in the flue gas to the water through the action of a hydraulic machine. **Dry removal of converter flue gas dust** is more efficient, and power consumption is only about half of the wet dust removal system.

(6) ***Electric arc furnace steelmaking (EAF):***

The electric arc furnace (EAF) mainly uses scrap steel as raw materials and uses electricity as the main energy to produce steel. The electric arc furnace capacity can be divided into large, medium and small size. The other EAF is that using DRI as the raw material. The main energy-saving devices can be further installed with electric arc furnace include:

Waste heat recovering and dedusting technology of EAF fume: a technology for reducing the flue gas temperature through the waste heat recovery device, which not only increases the effective air volume of the dedusting fan, reduces the load of the air dedusting fan, protects the bag duster, and also recycles the heat to generate steam for production and life use.

Optimization of the power-supply for EAF: a technology combines the power supply technology with the steelmaking technology to make the power supply technical parameters meet the power demand of the steelmaking process.

(7) ***Casting and rolling process:***

In the casting process, molten steel is poured into water-cooled molds at a controlled rate, and the steel is drawn to a row of rolls. Finally, the steel is straightened and cut to the required length. In many China's mills, steelmaking and rolling are arranged together, namely, continuous casting and rolling. Continuous casting machine is divided into the common domestic continuous casting equipment and the international advanced continuous casting equipment. The continuous casting equipment can be installed with the energy-saving devices, including:

High-efficiency continuous casting: a technology attached to continuous casting machine for achieving high-speed, high operating rate, high continuous casting rate and low rate of leakage, and producing the slab without defects.

Hot-transportation and hot-charging process: a technology for keeping the billet being hot by adding a insulation device during the transportation.

After the continuous casting process, steel plate enters the hot-rolled process. The traditional hot-rolled equipment includes the conventional hot-rolled equipment, conventional slab continuous casting equipment. The advanced hot-rolled equipment includes the thin slab continuous casting technology and endless strip production technology. The hot-rolled equipment also can be installed with the energy-saving equipment.

Thin slab continuous casting: this technology combines the continuous casting machine with rolling mill. The high temperature casting billet can be directly rolled with this technology.

Technology for endless strip production (ESP): a technology can realize continuous rolling of billet in rolling mill or realize direct rolling of

continuous casting billet.

Low-temperature rolling: a technology for rolling at lower temperature than the normal hot rolling temperature.

Regenerative combustion technology: a technology for waste heat recovery, whose core is high temperature air combustion.

After the processing of hot rolled steel, some hot rolled steel will be cooled into cold rolled steel. The **cold rolling process** can further reduce the thickness of the steel plate and improve the characteristics of the steel.

In the overall steel production process, we can control the whole industrial production processes by utilizing control and management system of energy. The **Control and management system of energy** is a technology that can improve and optimize the energy balance by implementing dynamic monitoring and management of energy production, transmission, distribution, and consumption in the enterprise, thus realizing systematic energy savings.

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